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Radioactive ^{26}Al and ^{60}Fe in the Milky Way: implications of the RHESSI detection of ^{60}Fe

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Abstract. The recent detection of gamma-ray lines from radioactive ^{26}Al and ^{60}Fe in the Milky Way by the RHESSI satellite calls for a reassessment of the production sites of those nuclides. The observed gamma-ray line flux ratio is in agreement with calculations of nucleosynthesis in massive stars, exploding as SNII (Woosley and Weaver 1995); in the light of those results, this observation would suggest then that SNII are the major sources of ^{26}Al in the Milky Way, since no other conceivable source produces substantial amounts of ^{60}Fe. However, more recent theoretical studies find that SNII produce much higher ^{60}Fe/^{26}Al ratios than previously thought and, therefore, they cannot be the major ^{26}Al sources in the Galaxy (otherwise ^{60}Fe would be detected long ago, with a line flux similar to the one of ^{26}Al). Wolf-Rayet stars, ejecting ^{26}Al (but not ^{60}Fe) in their stellar winds, appear then as a most natural candidate. We point out, however, that this scenario faces also an important difficulty. Forthcoming results of ESA's INTEGRAL satellite, as well as consistent calculations of nucleosynthesis in massive stars (including stars of initial masses as high as 100 $M_\odot$ and metallicities up to 3 $Z_\odot$), are required to settle the issue.

Key words. Galaxies: Milky Way

1. Introduction

^{26}Al is the first radioactive nucleus ever detected in the Galaxy through its characteristic gamma-ray line signature, at 1.8 MeV (Mahoney et al. 1982). Taking into account its short lifetime ($\sim$1 Myr), its detection convincingly demonstrates that nucleosynthesis is still active in the Milky Way (Clayton 1984). The detected flux ($\sim$4 10^{-4} cm^{-2} s^{-1}) corresponds to $\sim$2 $M_\odot$ of ^{26}Al currently present in the ISM (and produced per Myr, assuming a steady state situation). The COMPTEL instrument aboard CGRO mapped the 1.8 MeV emission in the Milky Way and found it to be irregular, with prominent "hot-spots" probably associated with the spiral arms (Diehl et al. 1995). The spatial distribution of ^{26}Al suggests that massive stars are at its origin (Prantzos 1991, 1993, Prantzos and Diehl 1996). However, it is not yet clear whether the majority of observed ^{26}Al originates from the winds of the most massive stars (i.e. above 30 $M_\odot$, evolving as Wolf-Rayet stars) or from the explosions of less massive stars (i.e. in the 12-30 $M_\odot$ range, exploding as SNII); the uncertainties in the corresponding stellar yields are still quite large (see Sec. 2) and do not allow to conclude yet.

Clayton (1982) pointed out that SNII explosions produce another relatively short lived radioactivity, ^{60}Fe (lifetime $\sim$2 Myr). Since WR winds do not eject that isotope, the detection of its characteristic gamma-ray lines [1] in the Milky Way would constitute a strong argument for SNII being at the origin of ^{26}Al. Based on detailed nucleosynthesis calculations of SNII (from Woosley and Weaver 1995) Timmes et al. (1995) found that the expected gamma-ray line flux ratio of ^{60}Fe/^{26}Al (for each of the two lines of ^{60}Fe) is 0.16, if SNII are the only sources of ^{26}Al in the Milky Way.

The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) detected the galactic ^{26}Al emission at a flux level compatible with previous observations (Smith 2003a). Most recently, Smith (2003b) reported the first ever detection of the Galactic ^{60}Fe gamma-ray lines with RHESSI; their combined fluxes correspond to a significance level slightly higher than 3 σ. The line flux ratio ^{60}Fe/^{26}Al is found to be 0.16 (for each ^{60}Fe line), precisely at the level predicted by Times et al (1995) on the basis of Woosley and Weaver (1995) nucleosynthesis calculations.

This finding of RHESSI appears as an impressive confirmation of a theoretical prediction. However, more recent studies of SNII nucleosynthesis produce different values for the ^{60}Fe/^{26}Al ratio (see next section), considerably higher than the one of Timmes et al. (1995). Combined with the

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[1] At 1.117 and 1.332 MeV, resulting from the decay of its daughter nucleus ^{60}Co

RHESSI finding, the new theoretical results call for a reassessment of the ^{26}Al sources in the Milky Way. In this work we discuss those results and their implications. We argue that none of the proposed sources of ^{26}Al satisfies all observational constraints at present. Forthcoming observations by the INTEGRAL satellite, combined with a new generation of stellar nucleosynthesis models (for rotating massive stars up to 100 $M_\odot$ and metallicities up to 3 $Z_\odot$) will probably be required to settle the issue.

2. ^{26}Al and ^{60}Fe: revised yields and γ-ray line fluxes

Four different groups (to our knowledge) have performed calculations of nucleosynthesis in massive stars, estimating the amounts of both ^{26}Al and ^{60}Fe and covering a relatively extended grid of stellar masses: Thielemann et al. (1995), Woosley and Weaver (1995), Rauscher et al. (2002) and Limongi and Chieffi (2003). In the first case, however, presupernova calculations are made in pure He-cores and the amounts of hydrostatically produced ^{26}Al are seriously underestimated; therefore, those results are not discussed in the following.

The calculations of Woosley and Weaver (1995, hereafter WW95) and of Rauscher et al. (2002, hereafter RHHW02) are made with essentially the same stellar evolution code, but the latter benefit from improved stellar physics and, especially, an updated library of nuclear reaction rates. Thus, the RHHW02 results supersede those of WW95, at least for solar metallicity stars (WW95 is the only published work providing yields of radioactive nuclei for an extended grid of stellar metallicities). Both those calculations take into account neutrino-induced nucleosynthesis during the supernova explosion, which increases the ^{26}Al yield by about 40% on average (WW95).

Finally, the Limongi and Chieffi (2003, hereafter LC03) calculations are done with a different stellar evolution code but with essentially the same set of nuclear reaction rates as RHHW02 (the REACLIB library of Rauscher and Thielemann). They adopt a different treatment for the study of the explosion than RHHW02 and they do not take into account neutrino-induced nucleosynthesis.

The situation concerning the ^{26}Al and ^{60}Fe yields of those calculations is summarized in the first and second panel of Fig. 1, respectively. In the top panel, it is clearly seen that the ^{26}Al yields of RHHW02 are substantially smaller than those of WW95, by a factor two on average. That difference is obviously due to the different input physics adopted in the two studies.

The LC03 yields of ^{26}Al are even smaller than those of RHHW02, and that difference can be attributed, at least partially, to the neglect of the neutrino-induced nucleosynthesis in the former study. Note that, in order to account for the uncertainties of the supernova explosion LC03 study a range of explosion energies, and this affects (slightly) the ^{26}Al yield of their lowest mass stars. Note also the interesting "convergence" of the three calculations in the case of the 20 $M_\odot$ star, perhaps because the properties of that particular stellar mass are better constrained after the extensive study of SN1987A.

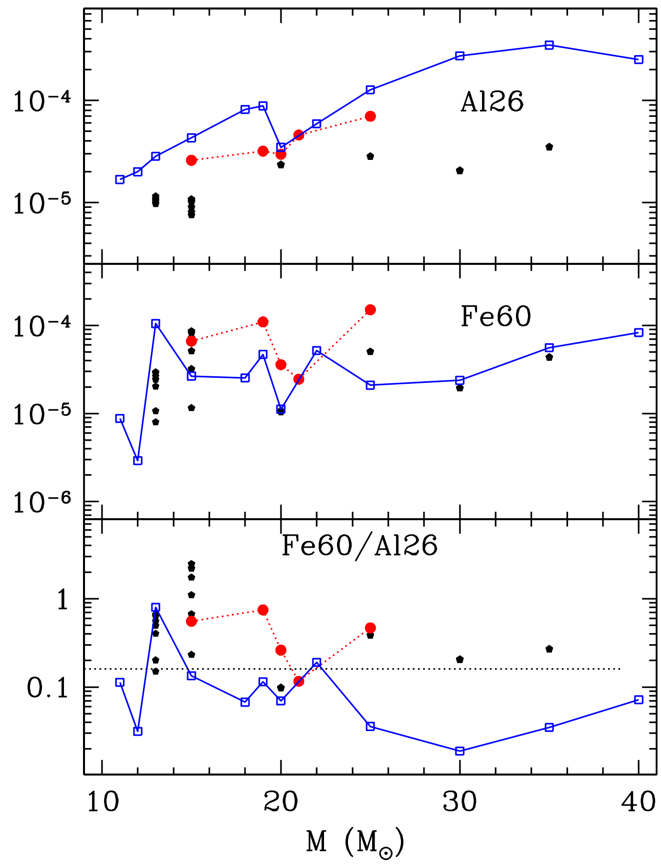

Fig. 1. Yields (in $M_\odot$) of ^{26}Al (*top*) and ^{60}Fe(*middle*) and the ^{60}Fe/^{26}Al gamma-ray line flux ratio (*bottom*) as a function of stellar mass, according to calculations by WW95 (*open squares* connected by solid lines), RHHW02 (*filled circles* connected by dotted lines) and LC03 (*filled pentagons*); in the latter case, different points for a given stellar mass correspond to different explosion energies. All calculations are for solar metallicity stars. The *dotted* line in the lowest panel corresponds to the RHESSI value of 0.16 (Smith 2003b).

In the case of ^{60}Fe, RHHW02 obtain yields twice as large as WW95, on average. The reason for that discrepancy is probably the improved library of nuclear reaction rates of RHHW02. Combined with the results for ^{26}Al, it becomes obvious that RHHW02 get ^{60}Fe/^{26}Al ratios four times larger than WW95. The corresponding results of LC03 are in excellent agreement with WW95 above 20 $M_\odot$ and in fair agreement with those of RHHW02. In the 13-15 $M_\odot$ range, the ^{60}Fe yields of LC03 depend strongly on the explosion energy, with the lower energies leading to higher yields. Note, however, that in all cases ^{60}Fe is produced by successive neutron captures on Fe-peak nuclei; the last step (^{59}Fe(n,γ)^{60}Fe involves the unstable nucleus (^{59}Fe, for which there are no experimental data concerning

its neutron capture cross-section. The nuclear uncertainties on its yield are thus quite important.[2]

The corresponding ratio of ^{60}Fe/^{26}Al by number (i.e. the yield ratio divided by 60/26) for each stellar mass appears in the bottom panel of Fig. 1. The results of WW95 are, on average, close to the value of 0.16 (dotted horizontal line), mentioned in the RHESSI discovery report of ^{60}Fe (Smith 2003b), while those of RHHW02 and LC03 are substantially above that value for almost all the stellar masses.

To compare properly with observations, these yields should be convolved with a stellar Initial Mass Function (IMF) and we adopt here the Salpeter IMF, a power-law[3] with slope x=-1.35, in order to obtain the number ratio

$$R(M_{UP}) = \int_{12M_\odot}^{M_{UP}} \frac{Y_{60}(M)}{Y_{26}(M)} \frac{26}{60} \Phi(M)\, dM \qquad (1)$$

as a function of the upper limit of integration M_{UP}. The results are plotted on Fig. 2. In the case of LC03 two curves are shown: LC03H corresponds to the high ^{60}Fe yields (low explosion energies) and LC03L to the low ^{60}Fe yields (high explosion energies). In all cases the thick portions of the curves correspond to the stellar mass range covered by each study, while the filled hexagons mark the highest mass of each calculation and thus provide the IMF weighted value over the whole mass range covered by each study.

The WW95 yields, integrated up to the highest mass of that study (M_{UP}=40 $M_\odot$) lead to a number ratio ^{60}Fe/^{26}Al=0.18, i.e. very close to the value 0.16 advanced by Timmes et al. (1995) on the basis of those same yields and the same IMF. It is precisely that theoretical prediction, well within reach of modern instruments, that made ^{60}Fe a prime target for astrophysical gamma-ray spectroscopy. The RHESSI discovery apparently confirms that prediction. However, an inspection of the more recent results shows that the modern theoretical expectations are, in fact, much higher: near unity for RHHW02 and LC03H and above 0.4 in the case of LC03L. In the light of those results, the RHESSI discovery at the level predicted by Timmes et al. (1995) looks more as a coincidence.

Assuming that the recent theoretical results are not to be substantially revised in the future and that the RHESSI result is confirmed,what are the implications for our understanding of the origin of ^{26}Al? The obvious conclusion is that the bulk of galactic ^{26}Al, detected by various instruments including RHESSI, is not produced by the source of ^{60}Fe: if this were the case, then ^{60}Fe would be detected with a line flux similar to the one of ^{26}Al. Obviously, another source of ^{26}Al is required, producing much smaller ^{60}Fe/^{26}Al ratios than the SNII.

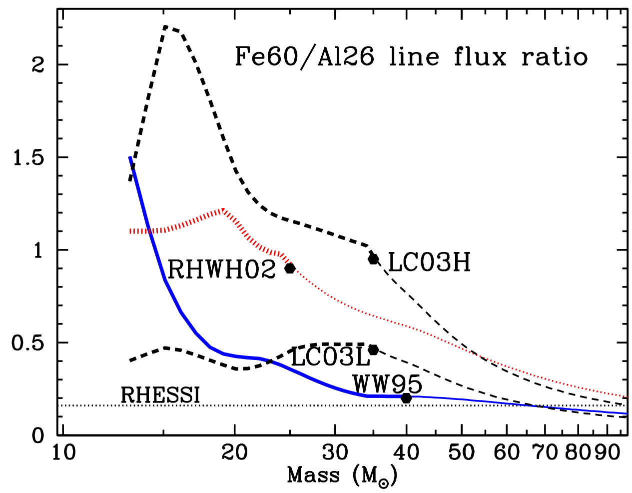

Fig. 2. The expected ratio of ^{60}Fe/^{26}Al decays (for each of the two ^{60}Fe lines), convolved with a Salpeter stellar Initial Mass Function, is shown as a function of the upper stellar mass limit of the convolution integral (see Equ. 1). The four curves correspond to the four different sets of stellar yields, with their thick portions corresponding to the mass range covered in those works (see text). The *dotted* horizontal line at 0.16 is the ^{60}Fe/^{26}Al ratio reported by RHESSI. *Filled pentagons* mark the upper mass in each of the four studies; all recent calculations predict much higher values than the older calculations of WW95 or the observed value of RHESSI. Only by taking into account the ^{26}Al yields of massive Wolf-Rayet stars (*thin* portion of the curves beyond the masses indicated by the filled pentagons, obtained by adding data for WR stars from Meynet et al. 1997) one may obtain ^{60}Fe/^{26}Al ratios compatible with the RHESSI results.

The obvious candidate source is Wolf-Rayet stars, as has been argued in many places over the years (e.g. Dearborn and Blake 1985, Prantzos and Cassé 1986, Prantzos 1991 and 1993, Prantzos and Diehl 1996, Meynet et al. 1997, Knödlseder 1999). The winds of those massive, mass losing stars, eject large amounts of ^{26}Al produced through H-burning in the former convective core, *before* its radioactive decay (in stars with no mass loss, those quantities of ^{26}Al decay inside the stellar core before the final explosion and never get out of the star). Note that WR stars eject negligible amounts of ^{60}Fe, since that nucleus is produced at more advanced stages of the stellar evolution than ^{26}Al and there is no time for it to be ejected before the final explosion (e.g. Prantzos et al. 1987). However, no complete calculations of WR stars (i.e. of massive stars, say above 40 $M_\odot$, with mass loss and up to the final explosion) are available up to now. The calculations of Woosley et al. (1995) concern only the advanced evolution of massive He cores and ignore any contribution of the WR winds to the ^{26}Al yields (besides, it is difficult to link the mass of their calculated He cores to the mass of the corresponding main sequence stars). Thus, the total ^{26}Al and ^{60}Fe yields of those stars (i.e. the sum of the masses ejected by

[2] The WW95 yields are calculated with cross section value of 1.8 mb for the neutron capture on ^{59}Fe, where the RHHW02 and LC03 calculations adopt a value of 3.4 mb, see Woosley et al. (2003).

[3] A power-law IMF is defined (as a function of stellar mass M) as : $\Phi(M) = dN/dM = AM^{-(1+x)}$.

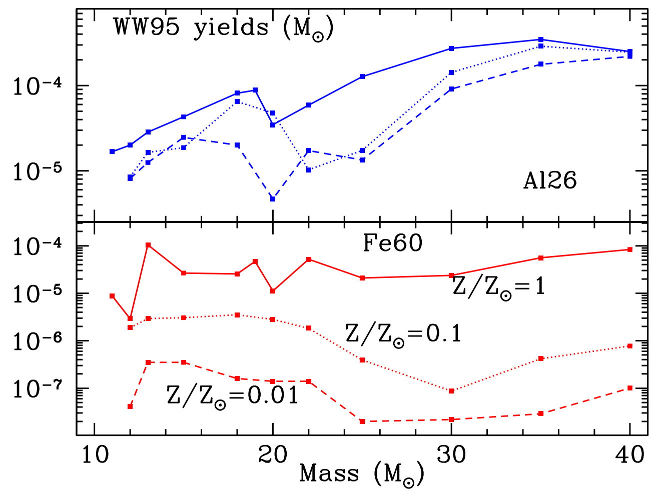

Fig. 3. Yields of SNII from WW95 for ^{26}Al (*top*) and ^{60}Fe (*bottom*), for three different values of the initial stellar metallicity (as indicated in the bottom panel).

the winds and by the explosion) is unknown at present. Although the number of such stars in a normal IMF is small, the amounts of ^{26}Al in the winds are extremely large and affect considerably the overall budget. In what follows, we assume that those stars eject negligible total amounts of ^{60}Fe (otherwise one faces the same problem with a high ^{60}Fe/^{26}Al ratio as before).

Adopting the ^{26}Al yields of non-rotating WR stars of solar initial metallicity by Meynet et al (1997), which concern stars of solar metallicity in the 25-120 M$_\odot$ mass range, and combining them with the aforementioned SNII yields, one obtains the ^{60}Fe/^{26}Al ratio expected by the total mass range of massive stars, during all the stages of their evolution; this is expressed in Fig. 2 by the continuation of the four theoretical curves above the masses indicated by the filled pentagons. It can be seen that the RHESSI result is recovered in that case, provided that at least half of ^{26}Al originates from WR stars (in the case of LC03L), or even that 80% of ^{26}Al originates from WR stars (in the case of RHHW02 or LC03H).

At this point, it should be noted that the aforementioned yields are not the most appropriate for a discussion of the galactic ^{60}Fe/^{26}Al ratio. Indeed, the metallicity gradient observed in the Milky Way disk (-0.07 dex/kpc for oxygen and several other metals, see Hou et al. 2001 and references therein) implies an average metallicity of around 2 Z$_\odot$ in the present-day disk. As already noted in several studies (e.g. Prantzos and Cassé 1986), it is the yields of stars with such a metallicity that contribute mostly to the metal enrichment of the Milky Way today.

Unfortunately, the works of RHHW02 and LC03 cover only solar metallicity stars, while the WW95 study considers a range of stellar metallicities below solar. One may, however, extrapolate from the trends obtained in the WW95 study at 2 Z$_\odot$ and scale accordingly the recent yields of RHHW02 and LC03. The WW95 yields for stars of initial metallicities Z$_\odot$, 0.1 Z$_\odot$ and 0.01 Z$_\odot$ are displayed in Fig. 3, for ^{26}Al (upper panel) and for ^{60}Fe (lower panel), respectively. It can be easily see that the ^{60}Fe yields are systematically proportional to the initial stellar metallicity for most stellar masses; the reason is that ^{60}Fe is mostly produced by neutron captures in the carbon shell and its yield is proportional to the initial ^{56}Fe amount. On the other hand, the yields of ^{26}Al are slightly higher at Z$_\odot$ than at 0.1 Z$_\odot$. Part of ^{26}Al is produced in the H-shell by proton captures on initial ^{25}Mg and this does depend on initial metallicity; however, the bulk is produced in the C-shell (more than 80% in the 25 M$_\odot$ star; see, e.g. Fig. 1 in Timmes et al. 1995) , where ^{25}Mg is produced by ^{12}C, itself resulting from the initial H and He of the star, and thus it is independent of the initial metallicity.

One concludes then that at 2 Z$_\odot$ the ^{60}Fe yields of SNII (i.e. stars in the 12-25 M$_\odot$ range) should be on average twice the corresponding ones at Z$_\odot$, while the ^{26}Al yields should be only slightly higher than their counterparts at Z$_\odot$. This implies in turn that the curves of ^{60}Fe/^{26}Al displayed in Fig. 2 (corresponding to Z$_\odot$ stars) are in fact lower limits to the values expected from the galactic population of massive stars [4]. This only exacerbates the discrepancy between the RHESSI result and the theoretical expectations from SNII, and makes the ^{26}Al contribution of WR stars even more important. Since the ^{26}Al yields of WR stars increase with metallicity approximately as $Z^{1.5}$ or Z^2(see below), they can easily match the increased ^{60}Fe yields of SNII at 2 Z$_\odot$ and bring the average galactic ^{60}Fe/^{26}Al ratio close to the RHESSI value. These qualitative considerations should be substantiated, of course, by self-consistent calculations of rotating stars at metallicities higher than Z$_\odot$, extended as to cover all the advanced evolutionary phases, as well as the final explosion (see Heger et al. 2000 and Hirschi et al 2003 for preliminary results of such calculations).

There is another way to understand the implications of the revised yields for the ^{26}Al sources, which does not involve ^{60}Fe. Indeed, observations of the Galactic 1.8 MeV line by different instruments converge to a value of 4 10^{-4} photons/cm^2/s , which corresponds to a steady state value of 2 M$_\odot$ of ^{26}Al (produced per Myr) in the interstellar medium (e.g. Diehl et al. 1995, Prantzos and Diehl 1996, Diehl and Timmes 1998). The average ^{26}Al yield in the recent calculations of SNII is 2.5 10^{-5} M$_\odot$(compared to 10^{-4} M$_\odot$ in WW95). Taking into account the average SNII frequency observed in Sbc galaxies like our own (∼1-2 per century, Cappellaro et al. 2003) one sees that SNII may produce about 0.3-0.6 M$_\odot$ of ^{26}Al per Myr, i.e. about 15-30 % of the total amount inferred from observations. The necessity for another source of ^{26}Al becomes obvious again. On the basis of non-rotating stellar models, Meynet

[4] In Timmes et al. (1995) a detailed model is presented for the Galactic disk, but the WW95 yields are used and no explicit mention is made of the galactic metallicity gradient. Thus, the ratio of 0.16 is obviously an underestimate, based on yields of stars with metallicity not exceeding Z$_\odot$.

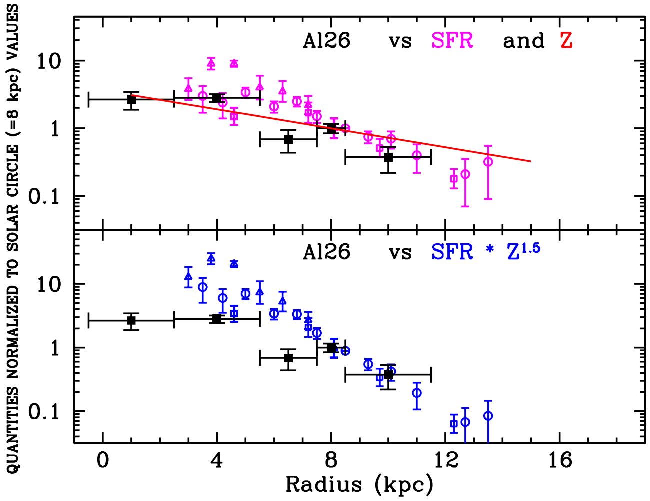

Fig. 4. Radial distributions of Al26, star formation rate (SFR) and metallicity (Z) in the Milky Way disk. *Upper panel:* Data points with vertical error bars correspond to various tracers of the SFR, while the galactic metallicity profile of oxygen (with a gradient of dlog(O/H)=-0.07 dex/kpc) is shown by a solid line; the Al26 profile, after an analysis of *COMPTEL* data by Knödlseder (1997), is shown (in relative units) by data points with vertical and horizontal error bars (the horizontal ones correspond to the adopted radial binning). *Lower panel:* If galactic Al26 originates mostly from WR stars, its radial distribution should scale with SFR * $Z^{1.5}$ (points with vertical error bars, scaled from the upper panel), since the Al26 yields of WR stars scale with $Z^{1.5}$ at least (Vuissoz et al. 2003, calculations for rotating stars); however, the observed Al26 distribution (same points as in upper panel) is flatter than the expected one in that case.

et al. (1997) show quantitatively that WR stars can indeed provide the bulk of galactic ^{26}Al. This is also supported by a different argument (Knödlseder 1999) concerning the similarity of the Galactic maps of ^{26}Al and of ionizing photon flux (provided only by the most massive stars, those that eventually become WR). Moreover, Knödlseder et al. (2001) point out that one of the prominent "hot-spots"of the COMPTEL 1.8 MeV map, the Cygnus region, is an association of very young massive stars, with no sign of recent supernova activity.

Those arguments point towards WR stars as major sources of ^{26}Al in the Milky Way. However, the situation is far from being clear yet, because the WR stellar yields of ^{26}Al depend strongly on metallicity. In the case of non rotating stellar models that dependence is $\propto Z^2$, according to Meynet et al. (1997). The rotating models of WR stars, currently calculated by the Geneva group (Meynet and Maeder 2003) show that rotation considerably alleviates the need for high mass loss rates, while at the same time leading to the production of even larger ^{26}Al yields than the non-rotating models (Vuissoz et al. 2003); in that case, it is found that the ^{26}Al yields of WR have a milder dependence on metallicity ($\propto Z^{1.5}$) than the non rotating ones. In both cases, that metallicity dependence of the ^{26}Al yields of WR stars, combined with the radial profiles of star formation rate (SFR) and of metallicity in the Milky Way (see Fig. 4, upper panel) suggest that the resulting radial profile of ^{26}Al should be much steeper than the one actually observed. The latter, derived from COMPTEL observations (Knödlseder 1997) appears in Fig. 4 (lower panel) and is clearly flatter than the product SFR*$Z^{1.5}$ (as already noticed in Prantzos 2002). Similar conclusions are reached if the longitude, rather than radial, profiles of ^{26}Al, metallicity and SFR are considered.

3. Conclusion

Contrary to a rather widely spread opinion, the recent RHESSI detection of radioactive ^{60}Fe in the Milky Way does not imply that ^{26}Al is mostly produced by supernova explosions. Recent theoretical results suggest that the ^{60}Fe line flux would then be close to the one of ^{26}Al (within a factor of two). Assuming that both the RHESSI results and the recent stellar nucleosynthesis results hold, another source of ^{26}Al should be found.

Wolf-Rayet stars appear as natural candidates, in view of their absolute ^{26}Al yields (at least in the framework of the Geneva models: either with high mass loss rates and no rotation - Meynet et al. 1997 - or with mild mass loss rates and rotation - Vuissoz et al. 2003) and presumably low ^{60}Fe/^{26}Al ratios. However, the strong dependence of the ^{26}Al yields on metallicity suggests that the ^{26}Al emissivity should be steeply increasing in the inner Galaxy, while the COMPTEL observations clearly display a milder enhancement at small Galactic longitudes.

Thus, almost twenty years after its discovery (Mahoney et al. 1982), the ^{26}Al emission of the Milky Way has not yet found a completely satisfactory explanation. Indeed, the recent observational (COMPTEL, RHESSI) and theoretical (RHHW02, LC03, Vuissoz et al. 2003) results have made the puzzle even more complex than before. The solution will obviously require progress in both directions. From the theory point of view, detailed nucleosynthesis calculations of mass losing and rotating stars up to the final explosion in the mass range 12-100 $M_\odot$ and for metallicities up to 3 $Z_\odot$ will be required ; furthermore, the uncertainties still affecting the reaction rates of ^{22}Ne(α,n) (major neutron producer during He burning in massive stars) and ^{59}Fe(n,γ) will have to be substantially reduced. From the observational point of view, the radial distributions of both ^{26}Al and ^{60}Fe will be needed; such distributions will probably be available if the operation of ESA's INTEGRAL satellite is prolonged for a few years beyond its nominal 2-year operation.

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